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On the Nature of the Progenitor of the Type Ia SN2011fe in M101

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ABSTRACT

The explosion of a Type Ia supernova, SN 2011ef, in the nearby Pinwheel galaxy (M101 at 6.4 Mpc) provides an opportunity to study pre-explosion images and search for the progenitor, which should consist of a white dwarf (WD), possibly surrounded by an accretion disk, in orbit with another star. We report on our use of deep *Chandra* observations to limit the luminosity and temperature of the pre-explosion white dwarf (WD). It is found that if the spectrum was a blackbody, then WDs of the highest possible temperatures and luminosities are excluded but, even if the WD was emitting at the Eddington luminosity, values of kT less than roughly 60 eV are permitted. This allows the progenitor to be an accreting nuclear-burning WD with an expanded photosphere. Pre-SN HST observations were used to derive a lower limit of about 10 eV for the expanded photosphere. Li et al. (2011) have already ruled out the possibility of a giant donor. We consider the combined emission from the WD, disk, and donor, and find that even the combined emission from a bright subgiant, WD and disk would not likely have been observed prior to explosion, and neither would some local candidates for the nuclear-burning WD model.

Subject headings: binaries: close – supernovae: general – X-rays: binaries

1. Introduction

Type Ia supernovae (SNe Ia) can serve as standardizable candles to large cosmological distances, and have enabled us to discover and study the acceleration of Universal expansion

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(Riess et al. 1998; Perlmutter et al. 1999). While there is a general consensus that an SN Ia results from the thermonuclear explosion of a carbon-oxygen white dwarf (WD) with mass approximately equal to the Chandrasekhar mass $M_{Ch} \sim 1.35 M_{\odot}$, and that the WD must have a companion that donated mass to it, the exact nature(s) of the companion and the mode(s) of mass transfer are still unknown (see Hillebrandt & Niemeyer 2000 for reviews). In single degenerate (SD) models, the WD accretes matter from its companion. The companion may be a main-sequence star, subgiant, or giant; it may fill its Roche lobe and/or donate mass through winds. In double degenerate (DD) models, matter is donated by another WD, and there may be a merger (e.g., Webblink 1984; Iben & Tutukov 1984).

The explosion of an SNe Ia (SN2011fe; Nugent et al. 2011) in M101, a well-studied galaxy located only 6.4 Mpc away (Shappee & Stanek 2011) allows us to search for the progenitor in pre-explosion images. Of special interest are *Chandra* observations from the Megasecond survey of M101 in 2003 (PI: Kuntz). SN2010fe was not detected in the *Chandra* images (Liu 2008, 2011), and our preliminary analysis placed an upper limit on X-ray luminosity of $3 - 5 \times 10^{35}$ erg s^{-1} (Soderberg et al. 2011). This upper limit is two orders of magnitude lower than for previous limits on other SNe Ia. In this paper we use the X-ray data to constrain the bolometric luminosity of the WD that was about to explode. We compute the expectations from each of several possible models, to interpret the significance of the lack of a detectable pre-SN X-ray source.

We also predict the level of optical emission that might be expected from an actively accreting WD and the disk that channels mass to it. This allows us to further test the accretion model by comparing the expectations with the results of pre-SN optical observations. Li et al. (2011) have used historical imaging to constrain the optical luminosity of the progenitor to be 10-100 times fainter than previous limits on other SN Ia progenitors. By doing so, they have ruled out luminous red giants and the vast majority of helium stars as the donor, and found that any evolved red companion must have been born with mass $\leq 3.5 M_{\odot}$. These observations favor a model where the pre-explosion WD of SN2011fe accreted matter either from another WD or by Roche lobe overflow from a subgiant or main-sequence companion star. We consider whether the optical observations place additional limits on the accretion model.

In §2 we outline the expectations based on both theoretical work and the results of prior observing programs. In §3, we use a blackbody with large ranges of bolometric luminosities and temperatures to represent the pre-SN WD, and check whether the pre-SN *Chandra* observations would have detected it. Additional constraints from pre-SN *HST* observations are also employed to constrain the expanded photosphere and the combination of donor and accretion disk. We discuss the implications of our results in §4.

2. Expectations

Theory predicts that WDs accreting in the range $\sim 3 - 6 \times 10^{-7} M_\odot$ yr^{-1} will burn the infalling mass in a more-or-less steady way, producing luminosities of $1 - 2 \times 10^{38}$ erg s^{-1}. If the radius of the photosphere is not too much larger than the radius of the WD, kT is expected to be $70 - 80$ eV or slightly higher (Nomoto et al. 1982; Iben 1982). Such sources can appear as luminous supersoft X-ray sources (SSSs; van den Heuvel et al. 1992; Rappaport et al. 1994). Di Stefano & Rappaport (1994) found that nuclear-burning WDs with these properties could be detected in external galaxies, unless there was an extraordinary amount of absorption. The amount of absorption expected in most locations in the face-on spiral galaxy M101, for example, would not obscure the X-ray emission from nuclear-burning near-M_{Ch} WDs, as long as the photosphere is comparable in size to the WD itself.

The possibility of detecting SNe Ia progenitors prior to explosion inspired searches with *Chandra* and *XMM-Newton* for bright, hot SSSs in external galaxies. An algorithm was developed and applied to about half a dozen early-type and late-type galaxies (Di Stefano et al. 2003; Kong & Di Stefano 2003). The results were that the numbers of SSSs in external galaxies of all types were at least one to two orders of magnitude smaller than required to support the hypothesis that the majority of SNe Ia derive from nuclear-burning WDs that are bright at X-ray wavelengths during the time they are accreting and burning matter (Di Stefano et al. 2006; Di Stefano et al. 2007; Di Stefano et al. 2009; Di Stefano et al. 2010ab). A study of diffuse emission in several early-type environments also found similar results (Gilfanov & Bogdan 2010).

The lack of SSSs is not evidence for a lack of nuclear-burning WDs. A modest change in photospheric radius would shift the spectrum to longer wavelengths, making the sources undetectable in X-ray. In fact, there is evidence that the local population of nuclear-burning WDs can switch "off" and "on" as SSSs when the photosphere expand or contract, even though their bolometric luminosity remains high (e.g., CAL 83, Greiner & Di Stefano 2002). A more direct test is to look for pre-SN X-ray emission from the locations of recent SNe Ia in nearby galaxies. There have been no reliable detections of pre-explosion X-rays from the site of an SN Ia. Upper limits for the X-ray luminosities have been dervived, most above a few $\times 10^{38}$ erg/s. Given these high upper limits, it is not possible to rule out pre-SN emission from a nuclear-burning WD (Nielsen et al. 2011).

3. Pre-SN *Chandra* and *HST* Observations

The location of SN2011fe was observed by *Chandra* ten times during 2003 (PI: Kuntz) (Table 1). The data were analyzed using uniform procedures in our Chandra/ACIS survey of nearby galaxies (Liu 2008,2011); SN2011fe was not detected in any of these observations. For this paper we merged the ten observations employing standard procedures. The location of SN2011fe has an equivalent total effective exposure time of 226 kiloseconds after vignetting corrections for individual observations (Table 1). Using CIAO 3.3, we ran *wavdetect* on the merged observation in the 0.3-8 keV band with scales of 1", 2", 4" and 8". No point source is detected at the location of SN2011fe, and no apparent feature is found by visual inspection.

The upper limit for SN2011fe is estimated by summing up photons from ten observations as listed in Table 1. Photon events are extracted from the SN2011fe location with three different circular apertures, which are the PSF enclosing 95% of the source photons at 0.5keV, 3.5" as the exposure weighted PSF size, and 5" as the PSF size for large off-axis angles. The background is carefully estimated from visually inspected surrounding annuli or nearby circular regions if the location is close to the chip edges. After background subtraction as listed in Table 1, we obtain a net count of -2.2 ± 2.6, -0.4 ± 2.6, and -3.1 ± 3.5 in the 0.3-8 keV for the three apertures respectively, or < 2.2 regardless the aperture chosen. Here the errors are computed from the number of photon counts N in the aperture as $\sigma = \sqrt{N}$. Because a progenitor could have a supersoft X-ray spectrum, we also estimate the photon counts in the 0.1-8 keV band. There are only a few photons below 0.3 keV at the location of SN2011fe, and we obtain a net count rate of -3.0 ± 2.8, 0.2 ± 2.6, and -3.9 ± 3.7 for the three apertures respectively in the 0.1-8 keV band, or < 2.8 regardless the aperture chosen.

To be conservative, we place an upper limit of 3 net counts for SN2011fe. Although the lack of photons below 0.3 keV may place stringent constraints on the supersoft X-ray spectrum of the progenitor, we choose to adopt the 0.3-8 keV band in the following because the instrument response below 0.3 keV is little known. This corresponds to a count rate of $\leq 1.3 \times 10^{-5}$ c/s, or a flux of $< 5.7 \times 10^{-17}$ erg/s/cm^2 (0.3-8 keV) assuming a $kT = 300eV$ blackbody spectrum and a foreground absorption of $n_H = 1.2 \times 10^{20}$ cm^{-2} (Dickey & Lockman), or a luminosity of $< 2.8 \times 10^{35}$ erg/s (0.3-8keV) given the distance of 6.4 Mpc (Shappee & Stanek 2011). Assuming a lower blackbody temperature of $kT = 100$ eV, this upper limit corresponds to a luminosity of $< 4.6 \times 10^{35}$ erg/s (0.3-8 keV). Assuming a power-law spectrum with $\Gamma = 1.7$ typical for X-ray binaries will lead to a luminosity of $< 4.9 \times 10^{35}$ erg/s in the 0.3-8 keV band.

The energy released through acretion and nuclear burning produce the bolometric luminosity. Emission in X-ray wavelengths would represent only a small fraction of the total, especially for SSSs. To link the count rate directly to bolometric luminosity and determine

accurately whether *Chandra* observations can constrain the pre-explosion WD of SN2011fe, we fold a blackbody spectrum through the Chandra/ACIS-S response matrix to estimate the net counts expected in 226 kilosecond using `fakeit` under the X-ray fitting package `xspec` 12.7.0e. Figure 1 shows the expected net counts for different blackbody temperatures and bolometric luminosities of $L_{bol} = 2 \times 10^{37}$, 2×10^{38} and 2×10^{39} erg/s. The bolometric luminosity of 2×10^{38} erg s^{-1} corresponds to the Eddington luminosity for a $M = M_{Ch}$ WD. The effective temperature for such a WD is expected to be 80-150 eV, and 32-600 net photons in 0.3-8 keV are expected. Given the photon count errors of $\sigma \leq 3$ and upper limit of ≤ 3 net counts for SN2011fe, such a hot WD can be excluded at the $\geq 10\sigma$ level.

In addition to the exclusion of a very hot WD, an important message of Figure 1 is the strong temperature dependence of the *Chandra* count rates. For $kT \leq 60$ eV, the count rate is so small that even a WD emitting at the Eddington luminosity may not have been detected in M101. We therefore compute the blackbody temperature above which the WD would have been detected by pre-SN *Chandra* observations with bolometric luminosities ranging from 10^{36} to a few $\times 10^{39}$ erg/s over a wide range of temperatures. This is plotted as a red solid curve for a detection threshold of 3 net counts in the upper part of Figure 2. This curve will move up slightly when adopting $n_H = 10^{21}$ cm^{-2}. Systems in the shaded region above this curve would have been detected by Chandra, and are thus ruled out by the non-detection. Systems in the unshaded region below this curve would not have been detected, and remain viable models. These include WDs burning matter at the Eddington rate, but emitting the radiation from an expanded photosphere with temperatures lower than 60 eV.

An expanded photosphere pushes the radiation to longer wavelengths and can therefore be constrained in the optical with pre-SN *HST* observations. As reported by Li et al. (2011), only upper limits can be derived for the progenitor. To obtain these limits, we photometer the *HST* observations, taken with ACS/WFC in three filters (F435W, F555W, F814W; PI: Kuntz), using the PSF-fitting package `dolphot` (Dolphin 2000). Based on the detected 2σ point-like objects on the same images, we derive the 2σ detection limits in STMAG as 28.3 mag, 28.0 mag and 27.5 mag in the F435W, F555W and F814W filters, respectively. Note that these limits are roughly 0.5 mag deeper than those derived by Li et al. (2011) because we use the PSF-fitting photometry in this dense stellar field, while Li et al. make very conservative estimates with the local background light.

To check whether the expanded photosphere would have been detected by pre-SN *HST* observations, its expected optical light is compared to the 2σ detection limits for *HST* observations as shown on the νF_ν plot in Figure 3. Based on this comparison, we compute the blackbody temperature below which the expanded photosphere would have been detected by *HST* observations for bolometric luminosities ranging from 10^{36} to a few $\times 10^{39}$ erg/s. This

is plotted as the blue dashed curve above the shaded region in the lower part of Figure 2. Clearly, the pre-SN *HST* observations would have detected an expanded photosphere with $L_{bol} = 2 \times 10^{38}$ erg/s and $kT \lesssim 10$eV, or an expanded photosphere with $L_{bol} = 3 \times 10^{37}$ erg/s and $kT \lesssim 5$eV in the shaded region, thus ruling them out. Models in the unshaded region above the dashed curve and below the solid curve could not be detected by either pre-SN *HST* or *Chandra* observations, thus can not be ruled out.

The accretion model can be further constrained when the optical light from the accretion disk and the donor is considered. Li et al. (2011) have shown that the donor could have been born with a mass no larger than $3.5M_{\odot}$. We consider a $2.5M_{\odot}$ subgiant, which by itself provides flux not too much below the *HST* limit. To compute the radiation from the disk, we consider a standard multi-color disk model but include the effects of irradiation (for a detailed discussion see Popham & Di Stefano 1996). Figure 3 shows an example of a realistic system, including radiation from the WD, the donor, and the disk, which cannot be ruled out. As shown in Figure 2, the addition of the accretion disk and the donor further excludes some expanded photosphere models that are allowed if only the photosphere is considered.

Nature has provided some realistic systems with all the above components, with some resembling the allowed models considered here. As shown in Table 2 and in Figure 2, the deep Chandra observations would have detected the M101 analog of the supersoft X-ray source CAL 87 in LMC (Greiner et al. 1991), and the recurrent nova RS Ophi in its supersoft phase during the outburst (e.g., Osborne et al. 2010). On the other hand, some other SSSs, if placed in M101, could not be detected by either Chandra or HST observations. These include CAL 83 with a high WD mass of $1.3 \pm 0.3M_{\odot}$ (Lanz et al. 2005) and RX J0537.7-7034 (Orio et al. 1997). Both SSSs exhibited X-ray on and off states on time scales of months to years.

Nielsen et al. (2011) found much lower luminosity limits for the same temperature, which would have detected even CAL 83. However, the X-ray to bolometric luminosity conversion factors they apparently used for spectral peak temperatures $T_{peak} = 30/50/100/150$ eV were actually the factors for the blackbody temperatures $T_{bb} = 30/50/100/150$ eV that correspond to $T_{peak} = 2.7 \times T_{bb}$. This will lead to bolometric luminosity upper limits $10^6/2000/16/4$ times lower. In addition, they used exposure maps for 30/50/100/150 eV, even though the Chandra/ACIS-S response matrix is not to be trusted or used below 0.3 keV. The approach we use here does not require use of the low-energy response matrix.

4. Discussion

Given its relative proximity and the extensive pre-SN observations, SN2011fe in M101 provides a unique opportunity to constrain the SNe Ia progenitor models. Unfortunately, though, in all SNe Ia progenitor models the pre-SN system is much dimmer than is typical for core collapse supernovae, making detection difficult. Even in SD models, which are relatively bright, the top bolometric luminosity of the WD is likely to be comparable to the Eddington luminosity, $\sim 2 \times 10^{38}$ erg s^{-1}. The disk will be dimmer, typically by one or two orders of magnitude. Unless the donor is a giant, a possibility ruled out by Li et al. (2011), it is expected to be much dimmer than the disk. Therefore, the existing data so far neither select a unique model nor rule out most models.

Nevertheless, important information has been derived that places limits on the progenitor system of SN2011fe. Li et al. (2011) rule out bright optical emission that would be associated with a giant or supergiant donor. In this paper we rule out 80 eV blackbody emission at 2×10^{38} erg s^{-1} at the $10\,\sigma$ level. This rules out that the progenitor WD was a Chandrasekhar mass WD accreting and burning matter at the maximum possible rate, with a photoshpere comparable in size to the WD's radius. Still allowed would be a nuclear-burning WD emitting at near Eddington luminosity with kT less than 60 eV but higher than 10 eV, or equivalently, with a photospheric radius 2-70 times the WD itself. The non-detections are also consistent with WD models with lower luminosities and slightly larger range of temperatures as shown by the unshaded region in Figure 2. Also allowed are some local candidates for nuclear burning WDs as listed in Table 2.

Other models with little X-ray emission cannot be rule out by existing pre-SN observations. A recurrent nova in quiescence, for example,has a luminosity of 10-100$L_\odot$ (e.g., Zamanov et al. 2010), and could not be detected by pre-SN observations. The pre-explosion WD in the DD scenario may also be dim in the epoch prior to explosion (Dan et al. 2011). A fast rotating WD spun up by the accretion in either the SD or DD models may exceed M_{Ch}, and will explode as SN Ia only when it spins down. This spin down phase may take a long time without accretion from the donor, thus no X-ray emission from hydrogen burning (e.g., Di Stefano et al. 2011).

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Table 1. Pre-SN *Chandra* Observations for SN2011fe[a]

OBsID	Texpt	OAA	PSF	VigF	Teff	C_{100}	C_{300}	B_{100}	B_{300}	BArea
4732.s3	70691	6.49	5.9	0.197	13926	1, 1, 1	1, 1, 1	23	17	400
4733.s3	25132	4.33	3.1	0.296	7439	0, 0, 1	0, 0, 1	23	21	400
4735.s3	29148	3.55	2.4	0.910	26525	0, 0, 0	0, 0, 0	19	14	300
5300.s3	52761	6.83	6.3	0.801	42262	4, 1, 2	4, 1, 2	30	28	300
5309.s3	71679	6.50	5.9	0.180	12902	1, 0, 1	1, 0, 1	30	24	400
5323.s3	43161	4.26	3.0	0.375	16185	1, 1, 2	0, 0, 1	12	12	400
5339.s3	14505	2.08	1.4	0.177	2567	0, 0, 1	0, 0, 1	8	6	300
6114.s3	67052	3.56	2.4	0.910	61017	1, 4, 4	1, 3, 3	75	63	300
6115.s3	36217	3.56	2.4	0.910	32957	0, 1, 1	0, 1, 1	15	13	300
6118.s3	11606	3.55	2.4	0.909	10550	0, 1, 1	0, 1, 1	9	7	300

[a]The columns are (1) Observation ID and the chip SN2011fe is on, (2) the exposure time of the observation in seconds, (3) off-axis angle in arcminutes, (4) the PSF size in arcseconds that encloses 95% of the photons at 0.5 keV, (5) the vignetting factor, (6) the vignetting-corrected effective exposure time, (7) the photon counts in the 0.1-8 keV band within separate PSFs for the ten observations, within 3.5" circles for all observations, and within 5" for all observations, (8) the three photon counts in the 0.3-8 keV band, (9) the background counts in the 0.1-8 keV band, (10) the background counts in the 0.3-8 keV bands, and (11) the area in pixels of the background regions used.

Table 2. Known sources with supersoft X-ray spectra[a]

Name[b]	Type	Period	kT	L_{bol}	Mv	B-V	Chandra?	HST?
CAL 83	CBSS	1.04	39-60	< 20	-1.3	-0.06	no	no
CAL 87	CBSS	0.44	63-84	60-200	0.1	0.1	yes	no
RX J0019.8+2156	CBSS	1.0-1.35	25-37	30-90	0.6	0.1	no	no
RX J0513.9-6951	CBSS	0.76	30-40	1-60	-2.0	-0.1	no	yes
RX J0537.7-7034	CBSS	0.13	18-70	6-20	1.0	-0.03	no	no
RS Ophi	RN	453.6	65-95	114-950	-5	0.5	yes	yes

[a]The information for the first five close binary supersoft sources (CBSS) are taken from Greiner et al. (1996). For the recurrent nova (RN) RS Ophi, the X-ray information in the brief (duty cycle: 1%) supersoft phase is taken from Osborne et al. (2011), the period is taken from Bandi et al. (2009), M_V and B-V during supesoft X-ray phase are taken from Hric et al. (2008).

[b]The columns are (1) the source name, (2) the source type, (3) the period in days, (4) the temperature in eV, (5) the bolometric luminosity in 10^{36} erg/s, (6) the absolute V magnitude, (7) B-V, (8) whether it would have been detected by pre-SN Chandra observations if placed in M101, and (9) whether it would have been detected by pre-SN HST observations.

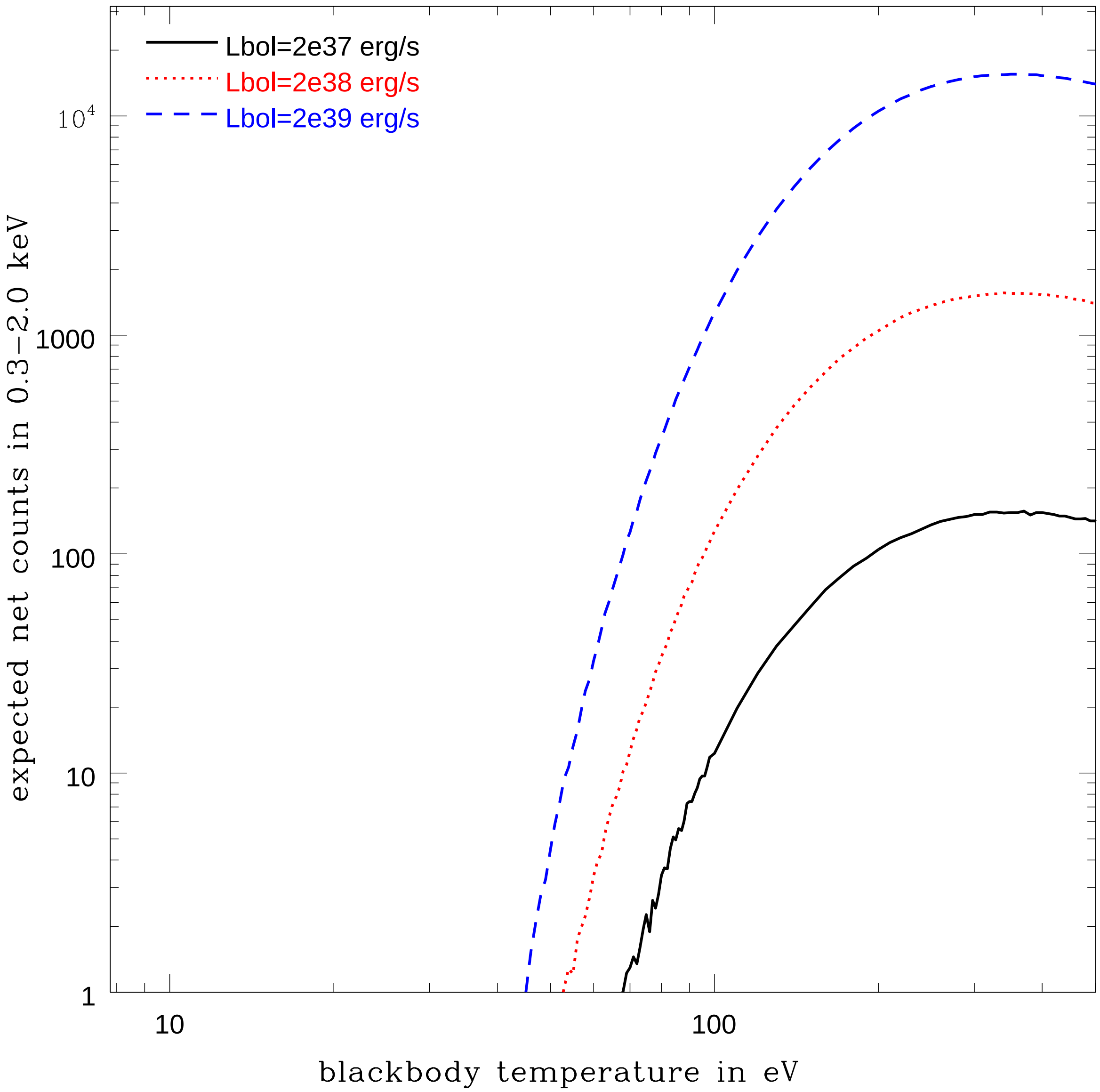

Fig. 1.— The expected net counts in 0.3-2.0 keV for a blackbody spectrum with different temperatures under bolometric luminosities of $L_{bol} = 2 \times 10^{37}$, 2×10^{38} and 2×10^{39} erg/s when observed by the merged pre-SN *Chandra* observations.

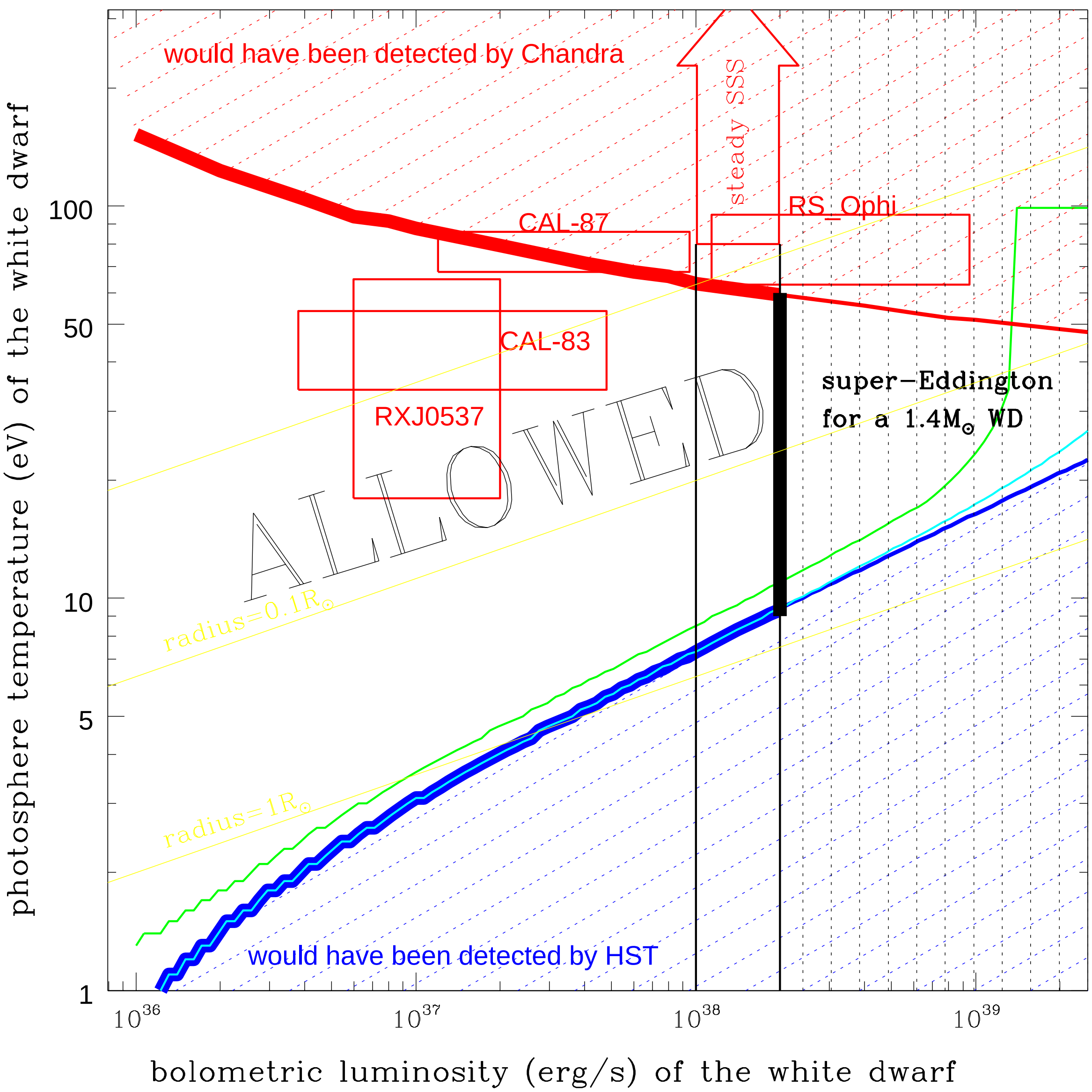

Fig. 2.— Constraints on the temperature and the bolometric luminosity of the pre-explosion WD by pre-SN *Chandra* and *HST* observations. The unshaded region to the left enclosed by the thickened curves represents models allowed by the non-detections in both *Chandra* and *HST* observations. The upper red thick solid curve stands for the temperature above which a blackbody would have been detected by pre-SN *Chandra* observations; the lower blue thick solid curve stands for the temperature of an expanded photosphere below which the photosphere would have been detected by pre-SN *HST* observations. Similar to the blue curve are the cyan line with optical light also from the irradiated accretion disk considered, and the green line with optical light also from the disk and the donor (an evolved star of $2.5M_{\odot}, 12R_{\odot}$ and 630Myrs old in this case) considered. The red arrow indicates the location of a $M = M_{Ch}$ WD with steady nuclear burning on its surface. The various boxes indicate the locations for known supersoft sources as listed in Table 2.

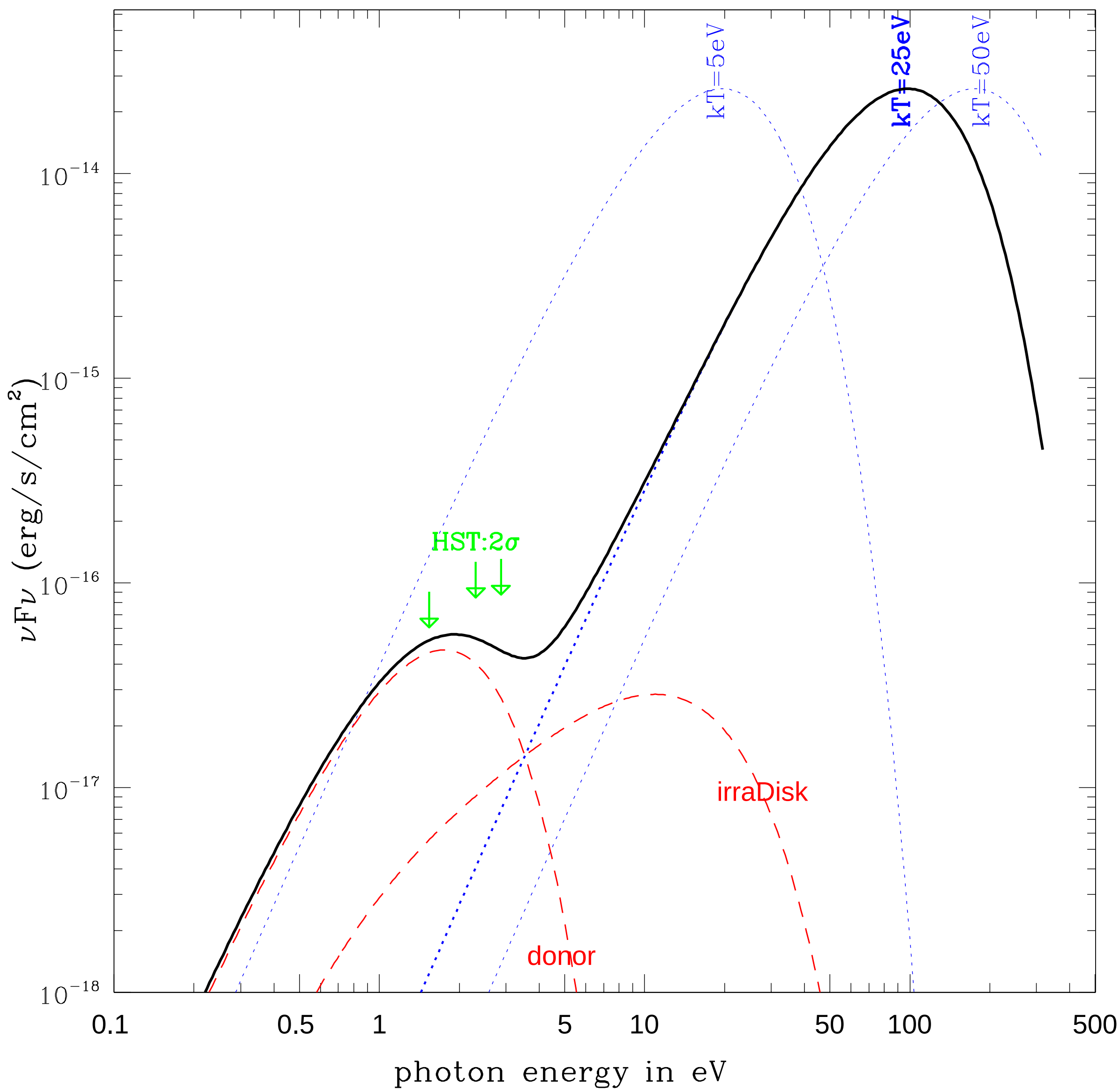

Fig. 3.— Expected optical light from different components of a possible SN2011fe progenitor as compared to the 2σ detection thresholds for pre-SN *HST* observations. The dotted curves stand for the spectra for an expanded photosphere with temperatures of 5 eV, 25 eV and 50 eV. The dashed curves, from left to right, stand for the spectrum for the donor (an evolved star of $2.5M_{\odot}, 12R_{\odot}$ and 630Myrs old in this case) and the spectrum for the irradiated accretion disk around a 25 eV photosphere. The solid curve stands for the summed radiation from the photosphere, the irradiated accretion disk, and the donor. Overplotted for comparison are known supersoft sources observed in the optical.